

Compound Chondrules fused Cold

Alexander Hubbard^{a,*}

^a*Department of Astrophysics, American Museum of Natural History, New York, NY 10024-5192, USA; Phone: 212-313-7911*

Abstract

About 4 – 5% of chondrules are compound: two separate chondrules stuck together. This is commonly believed to be the result of the two component chondrules having collided shortly after forming, while still molten. This allows high velocity impacts to result in sticking. However, at $T \sim 1100$ K, the temperature below which chondrules collide as solids (and hence usually bounce), coalescence times for droplets of appropriate composition are measured in tens of seconds. Even at 1025 K, at which temperature theory predicts that the chondrules must have collided extremely slowly to have stuck together, the coalescence time scale is still less than an hour. These coalescence time scales are too short for the collision of molten chondrules to explain the observed frequency of compound chondrules. We suggest instead a scenario where chondrules stuck together in slow collisions while fully solid; and the resulting chondrule pair was subsequently briefly heated to a temperature in the range of 900 – 1025 K. In that temperature window the coalescence time is finite but long, covering a span of hours to a decade. This is particularly interesting because those temperatures are precisely the critical window for thermally ionized MRI activity, so compound chondrules provide a possible probe into that vital regime.

Keywords:

Asteroids, Disks, Planetary formation, Solar Nebula

1. Introduction

Chondrules are sub-millimeter sized igneous inclusions found in chondritic meteorites which were melted in the Solar Nebula, the gas and dust disk from which our Solar System formed. Usually distinct objects within their host meteorite, they are sometimes found as part of a compound chondrule: two distinguishable chondrules fused together (see Figure 1). While compound chondrules (*ccs*, lower-case to distinguish from carbonaceous chondrites) are rare, with a frequency of about 4 – 5% of chondrules (Gooding & Keil, 1981; Ciesla et al., 2004), they are nonetheless common enough for some basic statistical information about their nature to be well established (Gooding & Keil, 1981; Wasson et al., 1995). Wasson et al. (1995) distinguishes between sibling and independent *ccs*, depending on whether the primary and secondary chondrules either have or don't have similar composition and textural types. One of the greatest difficulties in studying compound chondrules is the difficulty in correcting 2D information from thin sections to 3D properties (Ciesla et al., 2004), which makes determining their precise frequency difficult, and establishing other parameters, such as the size ratio of the secondary chondrule to the primary, fraught.

Gooding & Keil (1981) proposed that compound chondrules were made by collisions between still molten chondrules shortly after they were formed from ambient dust.

If so, then the *cc* frequency is an important constraint because it links the chondrule-chondrule relative velocity and cooling times to the chondrule number density (e.g. Desch et al., 2012). However, sibling and independent *ccs* occur at similar frequencies, implying that if the *cc* fusing process occurred at temperatures where the chondrules were molten, that process must have been able to maintain the structural integrity of droplets of nearly identical liquids in close contact with each other. This requirement is exacerbated by the observation that small contact angle *ccs* dominate the statistics (Wasson et al., 1995; Ciesla et al., 2004), i.e. the radius of the neck between the two component chondrules is generally much smaller than the radius of the individual chondrules, see Figure 2.

Wasson et al. (1995) suggests that at least some compound chondrules could have been made by melting nebular dust that had accreted onto a chondrule, which is a good model for enveloping *ccs*, a rare class of *ccs* so named because the second chondrule mostly envelopes the first. Miura et al. (2008) instead suggests a model where very large dust grains (far larger than observed chondrules) had their surfaces melted and stripped by a shock in the nebular gas. The stripped surface separated into droplets which in turn collided with each other, creating compound chondrules.

Excepting the production of enveloping *ccs* by melting an accretionary dust rim, the above models all require that molten droplets remain in contact, with very small contact angles, for significant collisional time scales. Note that we

*Corresponding author

Email address: ahubbard@amnh.org (Alexander Hubbard)

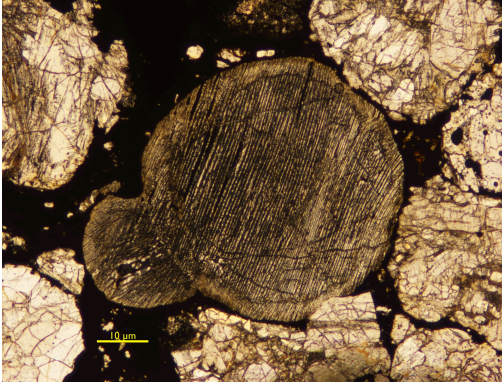


Figure 1: A plane polarized light micrograph of a compound chondrule from the Semarkona thin section AMNH 4128-1.

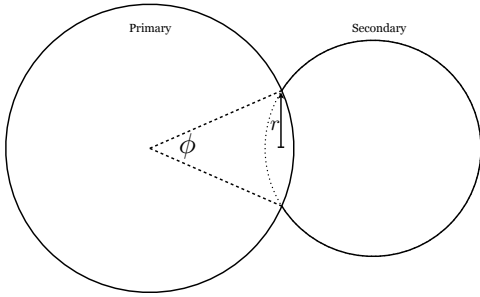


Figure 2: Cartoon of a compound chondrule. The neck of the bridge has radius r , while ϕ is the contact angle.

use the term “molten” to refer to chondrules sufficiently liquid that they collide as liquids, rather than solids. This is important because it allows the individual chondrules to collide at sufficiently elevated speeds that the observed *cc* frequency might be matched. In this paper, we consider only non-enveloping *ccs* and show that even at temperatures well below chondrule formation temperatures ($T \gtrsim 1700$ K, Hewins & Radomsky, 1990), droplet coalescence time scales are short compared to collisional time scales and that the molten-collision model cannot match the observed *cc* frequency. That means that the small contact angles observed are a major constraint, and imply that *cc* fusing had to occur relatively cold.

2. Viscosity and surface tension

Chondrules exhibit a range of sizes, compositions and textures (Weisberg, 1987; Wasson et al., 1995; Friedrich et al., 2014). Following previous studies of *ccs* (Ciesla et al., 2004; Desch et al., 2012), we adopt a characteristic chondrule radius of $a = 0.03$ cm, and a chondrule solid density $\rho = 3$ g cm $^{-3}$.

To understand the time scale on which molten chondrules in contact with each other would have flowed we

Table 1: H3 Chondrule Compositions

	BO	Average
SiO ₂	45.4	51.8
TiO ₂	0.21	0.14
Al ₂ O ₃	5.7	3.4
Cr ₂ O ₃	0.41	0.55
FeO	14.0	9.1
MnO	0.41	0.34
MgO	28.7	30.7
CaO	2.24	2.30
Na ₂ O	2.43	1.40
K ₂ O	0.45	0.17

need their surface tensions and viscosities. Chondrule melts had surface tensions on the order of

$$\gamma = 400 \text{ dyn cm}^{-1} \quad (1)$$

(or 0.4 N m^{-1} , Susa & Nakamoto, 2002).

We use Giordano et al. (2008) to calculate viscosities of chondrule melts¹. Weisberg (1987) lists the composition of chondrules found in ordinary chondrites (see Table 1). We find that the viscosities for barred olivine/average chondrules in ordinary chondrites were bracketed by the values of those chondrules in H3 chondrites:

$$\log \eta = -3.55 + \frac{4557.8}{T - 618.2} \quad (2)$$

and

$$\log \eta = -3.55 + \frac{5084.9}{T - 584.9} \quad (3)$$

for barred olivines and average chondrules, respectively. Barred olivines were less viscous for relevant temperature ranges (see Figure 3, left axis). T is the temperature in Kelvin and we are measuring the viscosity η in poise ($1 \text{ P} = 0.1 \text{ Pa}\cdot\text{s}$). While barred olivines are rare in the overall chondrule population (Gooding & Keil, 1981), using barred olivine compositions is not as strange as it might seem: Wasson et al. (1995) found that barred olivines are overrepresented in compound chondrules by a factor of many.

There is clear evidence that chondrules experienced multiple heating events (Jones & Danielson, 1997; Wasson & Rubin, 2003; Jones et al., 2005), and the existence of relict grains implies that at the temperatures we consider, many chondrules would have had more liquid, lower viscosity regions mixed with more solid, higher viscosity ones. However, as noted by Ciesla (2006), it is the lowest viscosity that controls the viscous behavior of the grains with the fluids flowing around the more solid inclusions.

Ciesla et al. (2004) found that chondrules behaved as liquids while colliding if their interaction time was longer

¹At the time of writing, a convenient on-line calculator can be found at <http://www.eos.ubc.ca/krussell/VISCOSITY/grdViscosity.html>

than the Maxwell time

$$\tau_M = \frac{\eta}{\mu}, \quad (4)$$

where $\mu \simeq 4 \times 10^{10}$ Pa is the shear modulus. They estimated the interaction time using Herztian contact theory, finding

$$t_{coll} = 2.87 \left(\frac{m_1 m_2}{m_1 + m_2} \right)^{\frac{2}{5}} \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)^{\frac{2}{5}} \left(\frac{a_1 + a_2}{a_1 a_2} \right)^{\frac{1}{5}} v, \quad (5)$$

where $m \simeq 3.4 \times 10^{-4}$ g, $\nu \simeq 0.25$, and $E \simeq 10^{11}$ Pa are the chondrules' masses, Poisson ratios and Young's moduli respectively. For those values, and a collision velocity $v_c = 100 \text{ cm s}^{-1}$, we can calculate

$$t_{coll} \simeq 3 \times 10^{-6} \text{ s}, \quad (6)$$

so the condition for liquid collision reduces to

$$\eta \lesssim \eta_{bc} = 10^6 \text{ P}. \quad (7)$$

That viscosity constraint implies

$$T > 1095 \text{ K}, \quad (8)$$

which value approximately applies for all collisional velocities as η is a very steep function of temperature and the critical η_{bc} value is a very weak function of v_c . Below that viscosity limit, or equivalently above that temperature limit, molten chondrules have a high sticking probability even at velocities above 100 cm s^{-1} . Below that temperature, chondrules collided as solids, bouncing unless the collisional speed was below 0.1 cm s^{-1} (Güttler et al., 2010).

3. Coalescence time scales

Liquid droplets in contact with each other tend to coalesce into a single droplet. This makes it problematic that liquid-sticking requires $\eta < \eta_{bc} = 10^6 \text{ P}$: we need the molten chondrules to have behaved as liquids for collisional interaction times, but not have behaved as liquids for far longer collisional or cooling windows.

As might be expected for a phenomenon with significant consequences for industry, there is a rich literature on droplet coalescence spreading (Frenkel, 1945; Tanner, 1979; Eggers et al., 1999; Yao et al., 2005; Aarts et al., 2005; Eddi et al., 2013). Viscous droplet coalescence or spreading time scales depend on a coalescence time scale:

$$\tau = \frac{a\eta}{\gamma}, \quad (9)$$

where a is the droplet radius (see Figure 3, right axis). This scaling can be understood on dimensional grounds: larger and more viscous droplets take longer to coalesce, while the surface tension provides the energy source, and

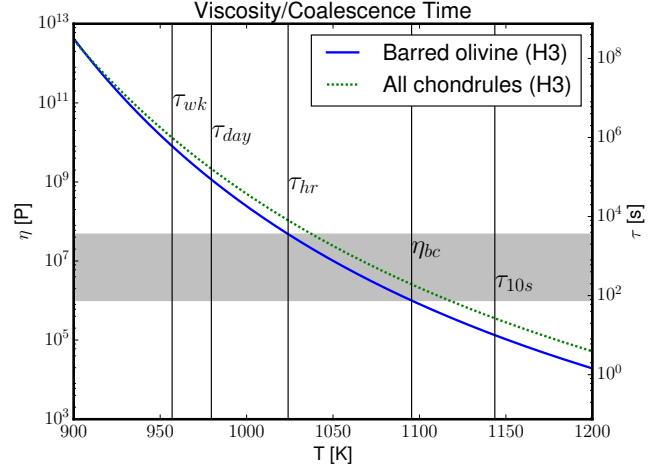


Figure 3: Viscosities (left axis) and coalescence times (right axis) for droplets with radii $a = 0.03$ cm. Solid/blue: H3 barred olivine chondrule composition. Dashed/green: H3 average chondrule composition. Vertical lines denote the temperature below which colliding BO chondrules bounce, and the temperatures at which BO chondrules have coalescence times τ of ten seconds, an hour, a day and a week. The shaded area separates the viscosities below which droplets are sufficiently molten to stick well from the viscosities above which the individual droplets are sufficiently solid to maintain their structural integrity for meaningful time scales.

τ is the combination of a , η and γ with the correct dimensions. One can also compare the energy dissipated by Stokes drag F_S on a sphere of radius a moving a distance a at a speed v through a medium of viscosity η to the surface energy of a droplet with surface area $\sim 4\pi a^2$ and surface tension γ :

$$aF_S = a \times 6\pi\eta av \sim 4\pi\gamma a^2, \quad (10)$$

and then estimate

$$\tau \sim \frac{a}{v} \sim \frac{a\eta}{\gamma}. \quad (11)$$

Calculating τ for $\eta = \eta_{bc}$ and $a = 0.03$ cm, we find $\tau = 75$ s.

The precise time dependence of the contact angle (or neck width) between two droplets remains a topic of research, but it is clear that there are multiple regimes where the radius of the interface between the droplets depends on τ^n for varying n , possibly with logarithmic corrections. However, it is nonetheless also clear from the literature that small contact angles can only be preserved for time scales

$$t \ll \tau, \quad (12)$$

which places an upper limit on how long molten chondrules can collide for. While this condition has the opposite implication as the plasticity time t_{plas} of previous work (Gooding & Keil, 1981; Ciesla et al., 2004), it enters into analyses of *cc* collision rates in the same fashion.

We should note that surface diffusion and sintering provides an alternate route to coalescence, but one with a characteristic time that scales as a^4 , significantly more

strongly than fluid coalescence with $\tau \propto a$ (Eggers, 1998). As such, it is expected to act relatively slowly on the scale of $a \simeq 0.03$ cm chondrules and indeed, extrapolating from Poppe (2003)’s data for SiO_2 spheres, surface diffusion acts far slower than liquid coalescence for the chondrules we are interested in.

4. Collisional compound chondrule formation

We can estimate the frequency of compound chondrules that resulted from collisions between molten chondrules, assuming perfect sticking:

$$f = n\sigma v_c t, \quad (13)$$

where f is the compound chondrule fraction, n the number density of molten chondrules, σ the chondrule-chondrule collisional cross section, v_c a characteristic collision speed and t the time window over which collisions lead to *ccs* fusing. Note that to avoid coalescence we require $t \ll \tau$.

For $a = 0.03$ cm chondrules,

$$\sigma = 4\pi (2 \times a)^2 \simeq 0.045 \text{ cm}^2. \quad (14)$$

At $R = 2.5$ AU (Desch, 2007), the Desch Minimum Mass Solar Nebula model provides a high end estimate for the gas density model of the Solar Nebula of $\rho_g = 2.3 \times 10^{-9} \text{ g cm}^{-3}$ at the midplane. An equal mass density in $a = 0.03$ cm, $\rho = 3 \text{ g cm}^{-3}$ chondrules implies

$$n \simeq 6.8 \times 10^{-8} \text{ cm}^{-3}. \quad (15)$$

Chondrule-sized dust grains are difficult to concentrate (see Jacquet et al. 2012; Hubbard & Ebel 2015, for discussions of dust concentration focusing on chondrules), so Equation (15) is a safe, significant over-estimate for the chondrule number density.

Using disaggregated chondrules, Gooding & Keil (1981) estimated that $\sim 4\%$ of chondrules are compound. Wasson et al. (1995) found a lower rate, $\sim 2.4\%$ by studying thin sections. Subsequently Ciesla et al. (2004) improved the 2D to 3D correction factors, finding instead 5% . We split the difference and use $f = 0.045$. However, this frequency is not the entire story. As noted by Gooding & Keil (1981) and especially by Wasson et al. (1995), compound chondrule do not appear to have been made by randomly picking two candidates from the pool of all chondrules and sticking them together. Radial pyroxene and barred olivine chondrules are heavily over-represented: combined they make up 97 of the 144 non-enveloping chondrules listed in Wasson et al. (1995)’s Table 7, despite making up only 10 – 13% of chondrules over all (Gooding & Keil, 1981). If this result holds, it implies that those chondrule classes have compound chondrule frequencies higher than the average by a factor of over 5, and $f = 0.045$ is an underestimate of the required *cc* frequency.

For viscosities below $\eta < \eta_{bc}$ (i.e. temperatures above $T > 1095$ K), chondrules collide as liquids, and can stick

even for elevated collisional velocities. However, at $T = 1095$ K, $\tau \simeq 75$ s, while at only slightly hotter temperatures, $T \simeq 1145$ K, $\tau = 10$ s. We require $t \ll \tau$ to avoid significant coalescence of the component chondrules into a single whole, and use $t = 10$ s as an overestimate, because it can only apply to chondrules which collide just above $T = 1095$ K. Chondrule precursors, loosely stuck together clumps of dust, could not survive collision speeds above $v_c = 100 \text{ cm s}^{-1}$ (Güttler et al., 2010), constraining the background chondrule-chondrule relative velocity. However, several km s^{-1} shocks, one of the proposed chondrule formation processes (Hood & Horanyi, 1991; Hood, 1998), can lead to significantly higher collision speeds (Nakamoto & Miura, 2004; Ciesla, 2006). Shocks capable of reaching the temperatures required for chondrule formation however also keep the chondrules above 1145 K for hundreds of seconds to tens of minutes or even longer (Boley et al., 2013; Stammer & Dullemond, 2014). This is many times the chondrule stopping time in the gas of under a minute, so in a shock-melting scenario, once the temperature had fallen below 1150 K, the chondrule relative velocity would have fallen far below the shock’s intrinsic velocity of several km s^{-1} . We therefore use $v_c = 10^4 \text{ cm s}^{-1}$ as an upper limit to chondrule relative velocities; while noting that restricting ourselves to temperatures in the range of 1095 – 1145 K and time scales of $t = 10$ s ignores the far longer time scales spent at higher temperatures, which would have yielded significantly more collisions. Those collisions would often have been destructive (Jacquet & Thompson, 2014), and even when they led to sticking, would have resulted in coalescence, rather than *cc* fusing.

Solving Equation (13) for f , using $t = 10$ s, $v_c = 10^4 \text{ cm s}^{-1}$ and the above values for n and σ , we find

$$f = 0.03. \quad (16)$$

While this is close to the observed value, it requires a significant overestimate in the chondrule number density. Further, it requires that all the collisions occur at temperatures above $T = 1095$ K but significantly below $T = 1145$ K while cooling out of that window on times neither much longer nor shorter than 10 s. Many chondrules experienced multiple heating events (Jones & Danielson, 1997; Wasson & Rubin, 2003; Jones et al., 2005), but any event which remelted a chondrule ($T \gtrsim 1700$ K) would have also led to coalescence, leaving only the *ccs* that fused following the final heating event. Accordingly, we can safely discount molten-chondrule collisions as a *cc* formation mechanism.

For viscosities above $\eta > \eta_{bc}$ (i.e. temperatures below $T < 1095$ K), chondrules collide as solids, and will only stick for collision velocities (Güttler et al., 2010)

$$v_c \lesssim 0.1 \text{ cm s}^{-1}. \quad (17)$$

Using Equation (13) to match $f = 0.045$ then requires

$$t \simeq 1.5 \times 10^6 \text{ s}, \quad (18)$$

or over two weeks. The requirement that $t \ll \tau$ then implies $T < 950$ K. Note further that we have overestimated n , and that the overall disk temperature at $R = 2.5$ AU was much colder than 950 K (Hayashi, 1981; Desch, 2007). In the solid-collision scenario it is far easier for the component chondrules to have collided at temperatures far below 950 K (with almost arbitrarily long time scales available) and been subsequently heated to temperatures above $T > 900$ K for just long enough for the first hints on coalescence to have occurred.

5. Conclusions

Figure 3 shows that for any reasonably warm temperature, there is a fusing time scale for chondrules in contact to form non-enveloping *ccs*. If the potential *cc* remained at that temperature for too short a time, then it would not have fused, while if it remained at that temperature too long the individual components would have coalesced. The molten-collision model for *cc* formation makes testable predictions about the temperature of the chondrules upon collision (they have survived the collision and stuck together) and the time scales available (sufficient *ccs* must have been produced). The shaded band in Figure 3 shows that if “molten” chondrules are sufficiently inviscid that they can behave as liquids upon collision and stick ($\eta < \eta_{bc}$), they are far too inviscid not to coalesce too fast for a sufficient number of compound chondrules to have been produced. This constraint does not depend on the precise temperature dependence of the viscosity η , only the critical viscosity η_{bc} above which chondrules collide as solid, not liquid, spheres, and hence is a robust result.

If compound chondrules could not have resulted from the collisions of molten chondrules, and indeed the primary and secondary chondrules could not ever have been in contact at temperatures significantly above ~ 1000 K, then they must be the result of chondrules colliding and sticking while cold. While naked chondrules are not expected to have been particularly sticky, experiments have shown that dusty rims could have bypassed that limitation (Beitz et al., 2012). Even so, sticking would have required low relative velocities, and hence the collision rate would have been very low, compensated for by almost arbitrarily long time scales chondrules could have spent floating freely and cold in the Solar Nebula.

In Figure 3, we have marked the temperatures for which the coalescence time τ is ten seconds, one hour, day and week, as well as the temperature below which bouncing is expected. The evidence that chondrules saw multiple heating events (Jones et al., 2005) implies that many such pairs of stuck together (but not yet fused together) chondrules would have experienced episodes of elevated temperature. If those episodes were a small but still respectable fraction of the coalescence time of their peak temperature, the component chondrules would have fused, but not coalesced,

leaving a *cc*. The temporal longevity and strength of temperature fluctuations in protoplanetary disks are not well understood, but it seems unlikely that a proto-compound chondrule could be held at temperatures above ~ 1025 K only for time scales short enough not to coalesce (no more than an hour). Similarly, it seems unlikely that a proto-*cc* could be held at temperatures just above, but only just above, 900 K for any significant fraction of the corresponding $\tau = 1$ decade, so at colder temperatures there would be inadequate spreading to allow *ccs* to fuse. We also know from noble gas measurements that only a modest fraction of the solids that were eventually incorporated into chondrites ever saw temperatures above ~ 800 K (Hubbard & Ebel, 2015), further constraining the ability to store proto-*ccs* in regions with $T > 800$ K for prolonged periods. We conclude that compound chondrules fused in a temperature window of 900 – 1025 K, with very finite dwell times.

The different viscosities expected for chondrules of average composition and BO chondrules (due to the later’s smaller SiO_2 fraction) could help explain one of the mysteries associated with *ccs*: the fraction of radial pyroxene and barred olivine chondrules in *ccs* appears to be several times higher than in the overall chondrule population (Wasson et al., 1995). If that result holds, the participant pairs in *ccs* were not selected at random. BO chondrules are expected to have been less viscous than an average chondrule (Figure 3), which means that they would have been more prone to spreading. That would have allowed BO chondrules to partially fuse and form *ccs* as a result of temperature fluctuations too weak to affect more viscous chondrules.

The frequency of compound chondrules cannot be used as a probe of the chondrule density in melting regions, as it has been used. However, with better statistics *ccs* could potentially be used as a probe of cold chondrule-chondrule sticking rates. This is important as chondrule agglomerations are an significant part of chondrite formation, and there are indications that chondrules did not dwell for long in chondrule forming regions (Hubbard & Ebel, 2015) after forming. Similarly, this means that *ccs* provide a potential probe for a new temperature window in the Solar nebula: noble gases in trapped in chondrite matrix (Huss & Lewis, 1994) and primary troilite in chondrules (Rubin et al., 1999) place upper experienced-temperature limits of about 800 and 650 K respectively, significantly colder than our 900 – 1025 K. This new temperature window is especially interesting as it lies near the ~ 1000 K threshold for thermal ionization to allow the magneto-rotational instability to operate (Gammie, 1996). These temperatures can also be further constrained by considering isotopic fractionation or lack thereof (Alexander et al., 2000) because our temperature window is close to the 50% condensation temperature of potassium in the Solar Nebula (~ 1006 K, Lodders, 2003).

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